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Relation between multipath and wave propagation attenuation

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A theoretical multi-slope wave propagation model is proposed based on ultra-wideband radio channel impulse response measurements in a dispersive channel. The theory, which applies to radiowave and acoustic propagation, relates multipath delay spread, propagation attenuation exponent, and the maximum possible rake gain for the multipath propagation channel.

Introduction: Recently measured high resolution ultra-wideband (UWB) channel impulse responses reveal different exponents in the distance dependence of the small area average for the total received energy and the energy of the strongest arriving pulse [1]. It is also found that the delay spread increases with distance [1]. In this Letter a simple theory is described to connect the differences in the propagation exponent with multipath scattering. This result has implications on receiving signals in multipath, rake gain and understanding the multipath wireless channel.

Propagation measurements: Propagation measurements were recently carried out in a large, single story building using an ultra-wideband (UWB) pulse transmitter and a UWB scanning receiver [2]. The measurement data was processed using the CLEAN algorithm [3] to extract the amplitude of the "strongest pulse" received in the energy delay profile, the total energy in the profile and the RMS delay spread of the profile. Scatter plots of the amplitude in dB of the strongest pulse and the total energy versus distance on a log scale between transmitter and receiver are shown in Figs. 1 and 2. The scatter plot of RMS delay spread τ_{RMS} versus distance on a linear scale is shown in Fig. 3.

The least squares fit line to the scatter plot, which is also shown in Fig. 1, indicates that the energy density of the strongest pulse $P_S(d)$ has a dependence on the distance d>1 between the transmitter and receiver of the form

$$P_S(d) = P_S(1)/d^3 \qquad (1)$$

having range index n_S=3. By comparison, the least square fit line to the total energy in the delay profile, which is shown in Fig. 2, indicates a range index n=2. Thus the density of the total received energy for effective radiated energy P_{EIRP} is given by

$$P(d) = P_{EIRP}/4\pi d^2 \qquad (2)$$

Finally, the distance dependence of the RMS delay spread τ_{RMS}, which is given by the least squares fit line in Fig. 3, is

$$\tau_{RMS}(d)=\tau_D d \qquad (3)$$

where τ_D=3 ns/m.

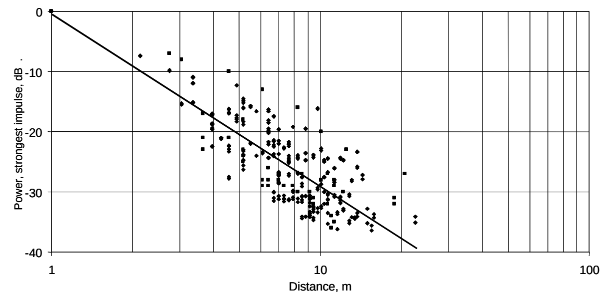

Fig. 1 *Strongest ray (pulse) power density versus distance.*
_____ median, curve fit
♦ data points

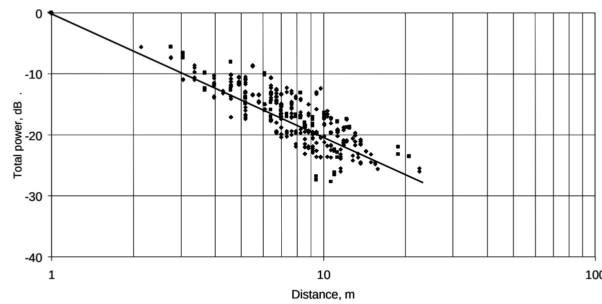

Fig. 2 *Total power density versus distance.*
_____ median, curve fit
♦ data points

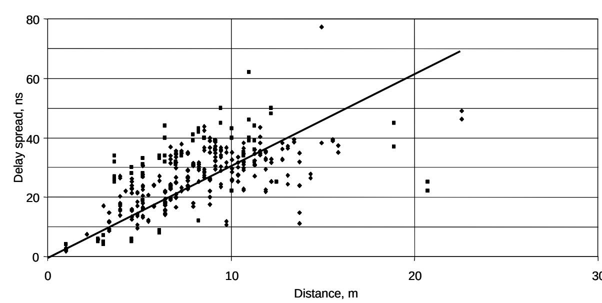

Fig. 3 *RMS delay spread versus distance.*
_____ median, curve fit
♦ data points

Theoretical Model: Ultra-wideband (UWB) pulses propagating through a physical environment, such as a large building, are scattered by the many obstacles they encounter. Creation of these multipath pulses removes energy from the primary pulse. The multipath pulses arrive at a receiver spread out in time, thereby creating the received time delay profile (received energy vs. time). Integrating the received energy over the entire delay profile gives the total received energy. The time resolution of UWB technology allows the separation of the direct pulse, which is the first arrival and usually the strongest pulse, from the rest of the received pulses.

Because of energy removed from the direct pulse by scattering, it is to be expected that the intensity of the direct pulse will decrease more rapidly with distance than the $1/d^2$ dependence in free space. At least for moderate distances d, the total energy flux will not be diminished by conversion to heat in the material encountered, and energy is conserved. Thus in a full 3D scattering environment, such as a large building, conservation of the energy flux leads to the dependence $1/d^2$, as seen in Fig. 2.

Energy delay profiles resulting from propagation inside buildings typically are a sequence of impulses arriving at discrete times $t=nt_0$ at an average interval $t_0 << \tau_{RMS}$. They have, on average, the classic exponential profile [4] of the form

$$S(d,t) = P_S(d)\sum_{n=0}^{\infty}\exp(-nt_0/t_{RMS})d(t-nt_0) \qquad (4)$$

The total energy $P(d)$ is found by integrating $S(d, t)$ over all time, which leads to the relation

$$P_S(d) = P(d)[1 - \exp(-t_0/\tau_{RMS})] \qquad (5)$$

between total energy, delay spread and strongest arrival energy. The value t_0/τ_D represents a breakpoint distance d_t in the range index and equals 1 in Fig. 1. For $t_0/\tau_{RMS}<1$, or $d>1$ in Fig. 1, the term in brackets can be replaced by the negative of the argument of the exponential in (5), and

$$P_S(d) = P(d)t_0/\tau_{RMS} = P(d)d_t/d \qquad (6)$$

This relation is satisfied by the distance dependencies observed for the measurements made in a large building, where $P(d)$ varies as $1/d^2$, τ_{RMS} varies as d and $P_S(d)$ varies as $1/d^3$.

For propagation in urban environments from base station antennas to mobiles the average delay spread is thought to vary as $\tau_{RMS} = \tau_C d^{\,0.5}$ where d is in km and τ_C, which is the average delay spread at 1 km, has a value in the range 0.4 – 1.0 μs [5]. For such radio links, the scattering environment is essentially a 2D layer of finite thickness, so that power scattered upward is lost. As a result, the average of the total power density in the scattering layer exhibits a distance dependence $1/d^n$ with $n>2$. Equations (5) and (6) suggests that the strongest arriving pulse will have distance dependence $1/d^{(n+0.5)}$. The difference in range index for the total power and strongest pulse power does not appear to have been measured directly, or discussed in the literature.

Relation to maximum rake gain: The maximum available RAKE gain is defined by the ratio of 'total energy density' to 'single impulse energy density'. When expressed in dB, and using (5), on average

$$G_{max}=10\log[P(d)/P_S(d)] = -10\log[1-\exp(-t_0/\tau_{RMS})] \qquad (7)$$

Based on the indoor measurements, and for $d>1$, $G_{max}=10\log(d/d_t)$, so that G_{max} increases with d as $10\log(d)$. However, in the case of cellular systems, the dependence of τ_{RMS} of $d^{\,0.5}$ will result in G_{max} increasing only as $5\log(d)$.

Propagation path model: A propagation model for the strongest impulse is based on the theory (5) with $t_0/\tau_{RMS}(d)=(d_t/d)^{n-2}$ where the range index beyond d_t is n. Path gain PG between 0 dBi antennas is weighted by receiver antenna aperture $c^2/4\pi f_m^{\,2}$, where f_m is the geometric mean of the low and high frequency band edges of the UWB pulse, and c is the velocity of propagation. The path gain is described by

$$PG = 10\log\{[c/4pdf_m]^2\,[1-\exp(-(d_t/d)^{n-2})]\} \qquad (8)$$

Equation (8) is especially useful for modeling propagation in short range indoor personal area networks as exemplified by the IEEE802.15.3 draft standard [6].

Conclusions: A theoretical basis for the propagation exponent in scattering was derived based on high resolution channel impulse response measurements. It is found that propagation measurements are dependent on how the energy is collected with respect to multipath and RAKE gain in the receiver. A general propagation model is proposed to show the close relationship between the propagation law, multipath delay spread, and rake gain. The model is particularly applicable to propagation in short range wireless personal area networks, and especially for UWB signals.

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